Using Spectrum Consumption Models to Manage Radar and Broadband Spectrum Sharing

John A. Stine

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Based on work performed with Sara MacDonald, Tony Soltyka, Alexe Leu, Sam Schmitz, and Darcy Swain-Walsh

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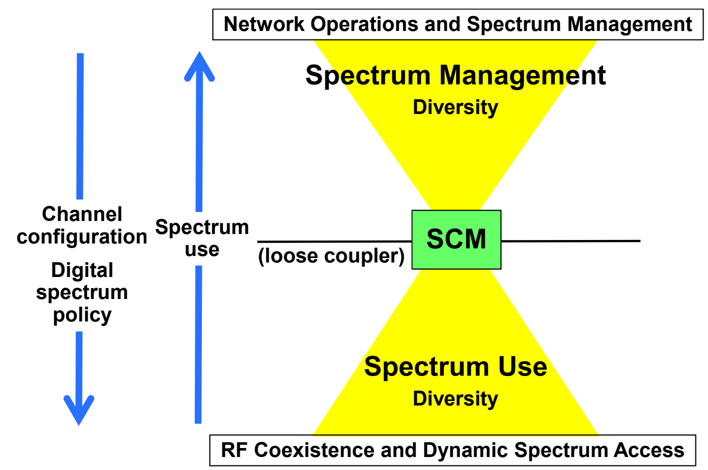
Agenda

- **Overview of Model-Based Spectrum Management**
- **Overview of Spectrum Consumption Modeling**
  - Constructs and what they capture
  - Assessing compatibility
- **Important characteristics of broadband and radar systems**
- **Capturing transmitter characteristics**
- **Capturing receiver characteristics**
- **Propagation**
- **Using policy and protocol**
- **Conclusion**

Model-Based Spectrum Management (MBSM)

- **Spectrum management (SM) based on the creation and exchange of spectrum consumption models (SCM)**
  - SCM capture the consumption of spectrum not the details of systems
  - SCM have attendant computations for assessing compatibility among models (A common means across the entire SM system)
  - SCM attempt to be a loose coupler for the SM system
    - The minimal amount of data at the intersection of the activities of SM
    - Captures the intent of users and the judgment of spectrum managers
    - Conveys spectrum use policy



- **MBSM seeks**
  - Greater resolution in spectrum management
  - More agile spectrum management (i.e. real-time)
  - Spectrum sharing
  - To provide policy-based spectrum management
  - To enable devices and systems to collaborate in spectrum sharing

12 Constructs for Building SCMs

- Total power
- Spectrum mask
- Underlay mask
- Power map
- Propagation map
- Intermodulation masks
- Platform
- Location
- Start time
- End time
- Minimum power spectral flux density
- Protocol or policy

Captures the spectral content of the signal and the unique characteristics of spread spectrum systems

Captures a definition of interference

Can capture antenna effects

Can capture environmental effects

Captures susceptibility to intermodulation

Enable greater resolution in spectrum management

Can capture behaviors that enable compatible reuse

Most constructs have probability data elements to declare confidence in parts that are variable or are uncertain

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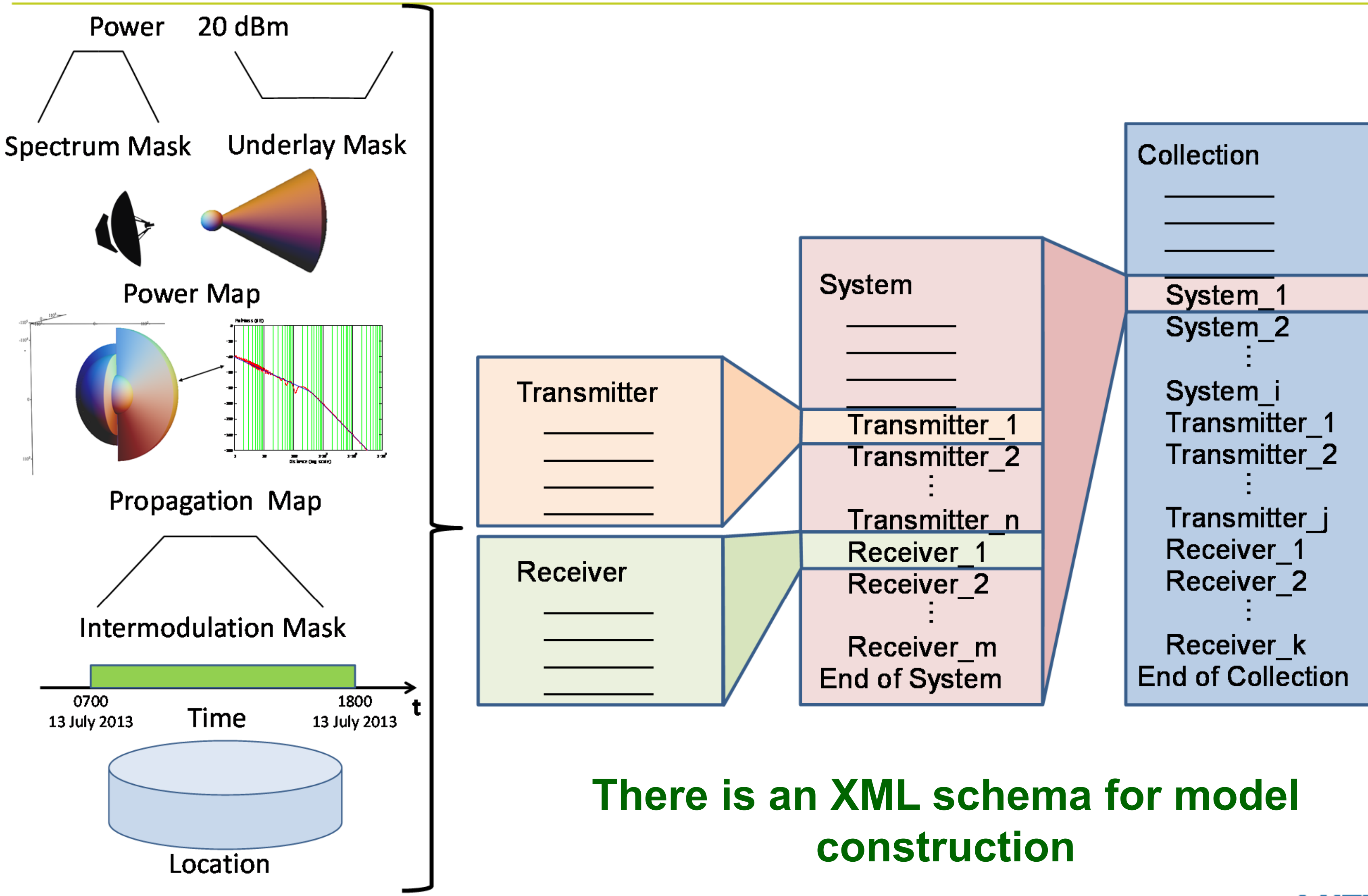
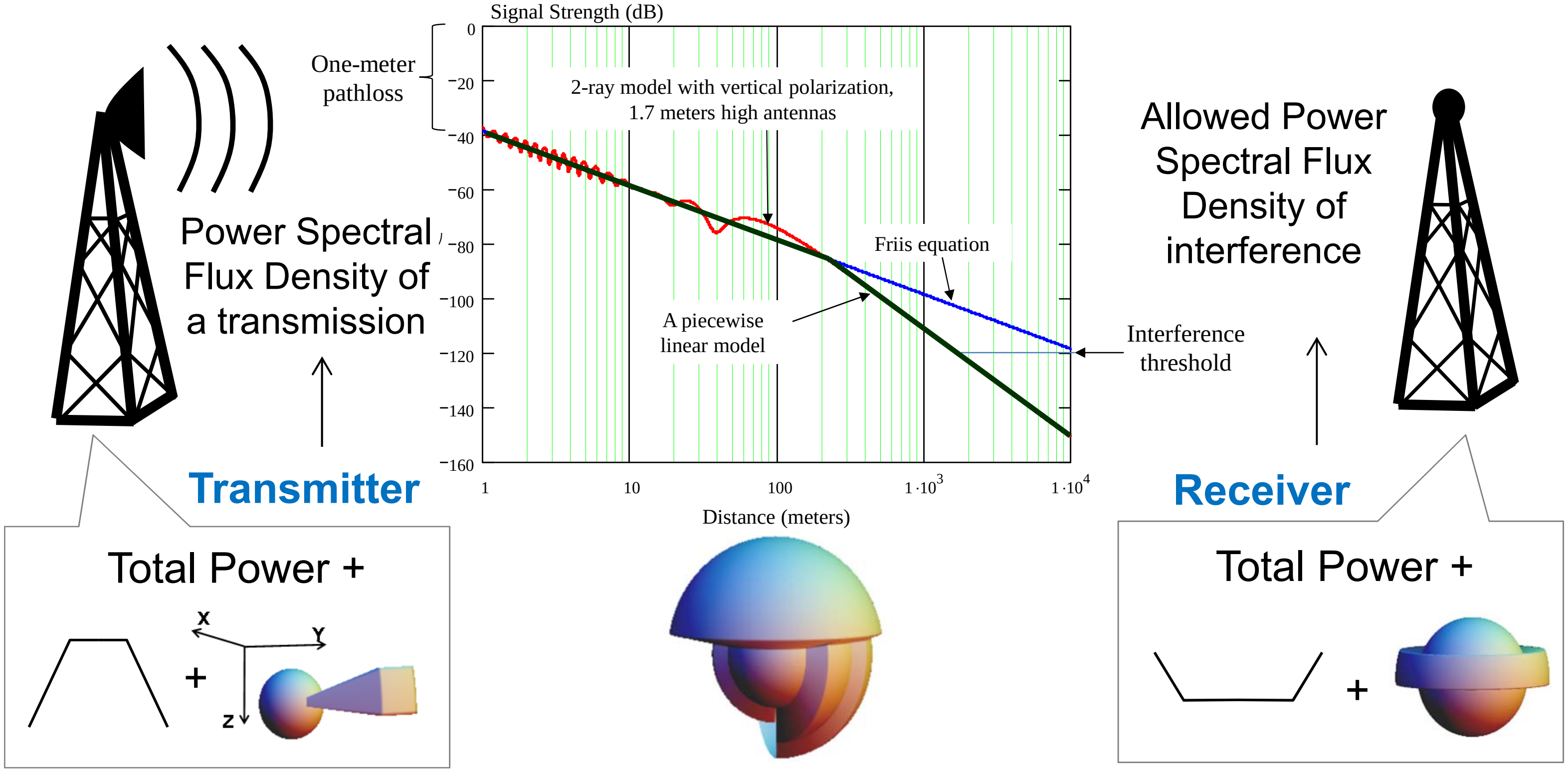
Combining Constructs into Models



There is an XML schema for model construction

Compatibility Computations



- **Constructs are a means to specify the factors that determine a link budget in all directions**
- **Modelers build SCMs to identify the power spectral flux density of transmissions and allowed interference**

SCMs are built to protect not to predict!

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The Link Budget

- **Link budget in a single direction**

$$TP_{rcvr} - TP_{tmtr} \geq PM_{Masks} + AG_{tmtr} + AG_{rcvr} + PL(d)$$

  - TP_{rcvr} – Total Power in the receiver model
  - TP_{tmtr} – Total power in the transmitter model
  - PM_{Masks} – Power margin resulting from the interaction of masks
  - AG_{tmtr} – Antenna gain from the transmitter power map
  - AG_{rcvr} – Antenna gain from the receiver power map
  - $PL(d)$ – Pathloss as a function of distance using a propagation map model
- **Unique computations**
  - Mask interactions
  - Constraining points (Considers all directions and locations)
  - Collective interference of multiple users

Broadband Systems

- **Sharing constraints, objectives, and assumptions**
  - Long term and continuous access
  - Small cell operation
  - Managed as part of a heterogeneous network
- **Key characteristics (What we want to model)**
  - Interference limited
  - Block coding is tolerant to some losses
  - Adaptive power levels
  - Fixed base station with mobile users
  - Broad front ends with narrow channels
  - Placed in environments with shielding from walls and structures

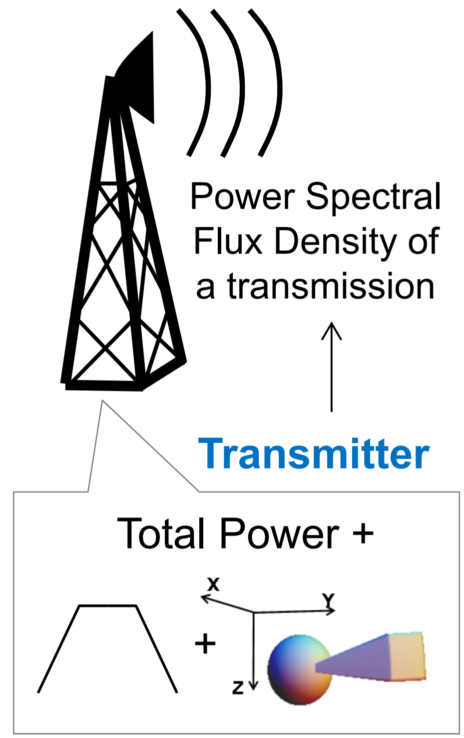
Radar Systems

- **Sharing constraints and objectives**
  - Obfuscation of operational and technical details
  - Flexibility to deviate from routine operations to the extreme quickly
- **Key characteristics (what we want to model)**
  - Mobile
  - High power
  - Pulsing low duty cycle signals
  - Highly directional antennas
  - Antenna scanning
  - Operational variation (scanning versus tracking)
  - Advanced signal processing to overcome countermeasures

Most Relevant Constructs and Their Details

Transmission Power Spectral Flux Density

- **Captured using three constructs**
  - Total power
  - Spectrum mask
  - Power map
- **May divide a model up into different spaces with each having a different set of constructs for power spectral flux density**
- **Systems having multiple transmitters**
  - Model each individually
  - Model a set of mobile transmitters (e.g. data links and mobile ad hoc networks) by a single model and a space



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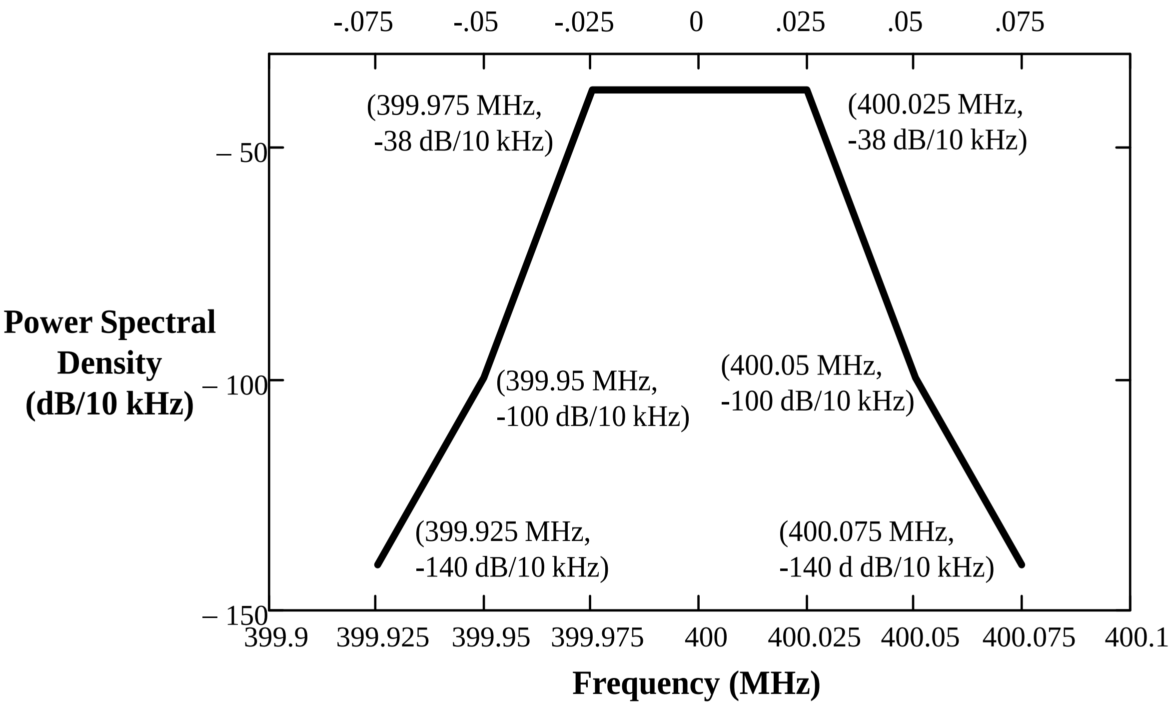
1 – Total Power

20 dBm

A reference value to which other model construct refer

2 – Spectrum Mask



A list of inflection points that form a mask. Each point consists of a frequency and relative power. A resolution bandwidth conveys the spectral density of the power terms, i.e. dB/BW.

Specifies the power-density spectrum of a signal

Actual frequencies: **(399.925, -140, 399.95, -100, 399.975, -38, 400.025, -38, 400.05, -100, 400.075, -140)**
BW = 10 kHz

Relative frequencies: **(-0.075, -140, -0.05, -100, -0.025, -38, 0.025, -38, 0.05, -100, 0.075, -140)**
***f* = 400 MHz, BW = 10 kHz**

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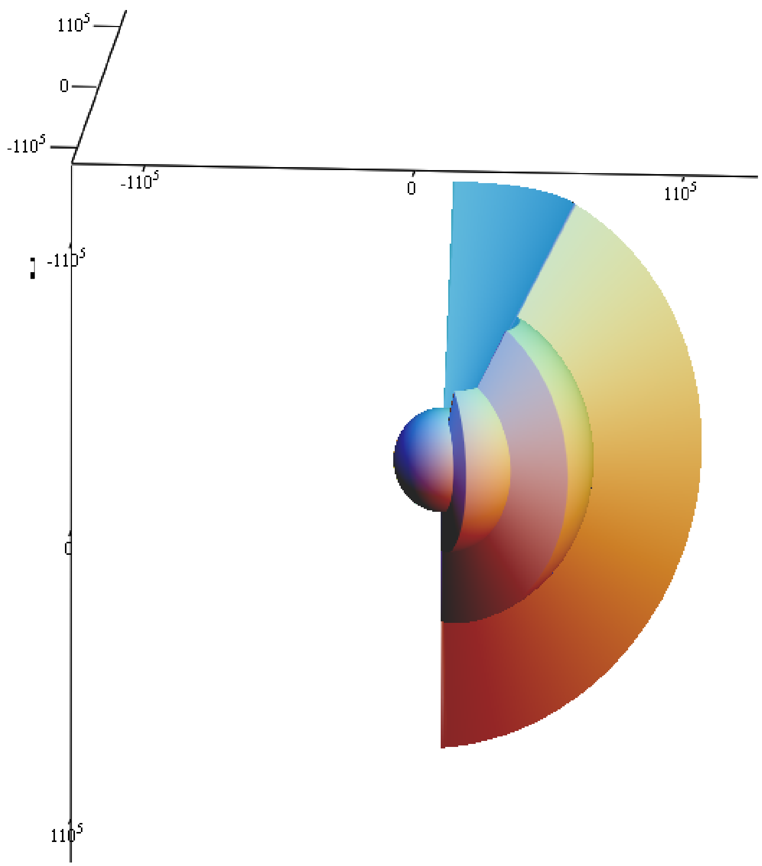
Spectrum Masks – Continued - 2

- **A spectrum mask conveys the spectral content of a signal**
- **Data Structure**
  - The basic mask is a (1 × n) array of real values alternating between frequency and power $(f_0, p_0, f_1, p_1, \cdots f_x, p_x)$
  - A relative mask specifies frequencies relative to a reference frequency $(\Delta f_0, p_0, \Delta f_1, p_1, \cdots \Delta f_x, p_x)$
  - Resolution bandwidth is a real value and applies to all power terms in a mask
- **Two versions**
  - Continuous signal – the mask stands alone, frequencies are actual
  - Frequency hopped and pulsed signal – the mask is accompanied by additional values, frequencies are relative to a center frequency
    - A center frequency list $(f_0, f_1, f_2, \cdots f_x)$ or a list of frequency bands, $(f_{b1}, f_{e1}, f_{b2}, f_{e2}, \cdots f_{bx}, f_{ex})$ where the pair (f_{b1}, f_{e1}) identify the beginning and ending frequencies of a frequency band
    - A dwell time
    - A revisit period

4 – Power Map



(-20, 70, -25, 120, -30, 160, -35, 360, 150, -35, 0)

A variable length *1* x n array that assigns power levels to solid angles about a point

Specifies the relative power density by direction

20 dB/m^2

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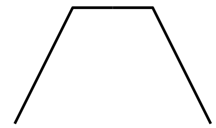
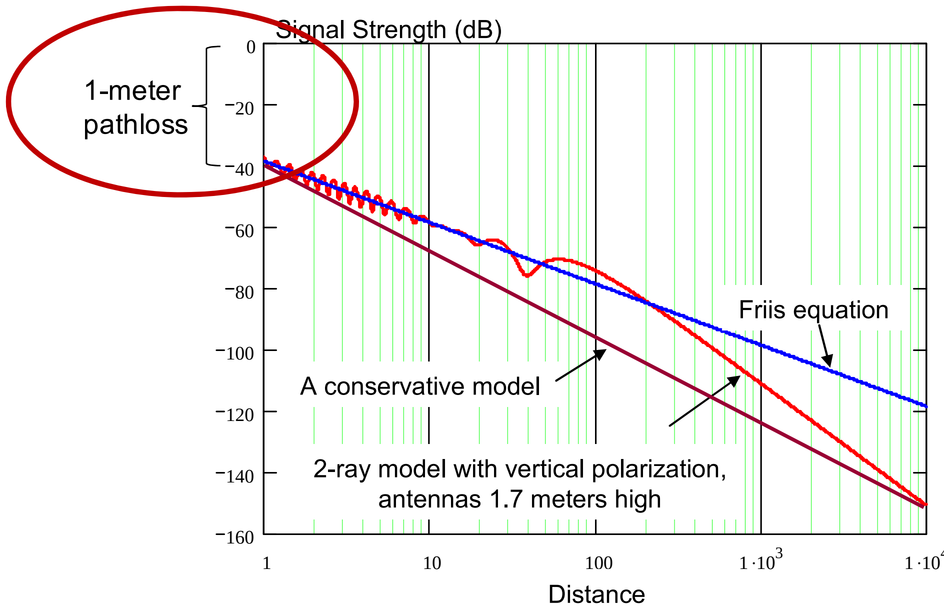
Power Map – Continued - 2

- **Provides a directional gain**
- **Together with the total power and spectrum mask specifies the power spectral flux density in a direction**
- **The direction power spectral flux density is used as the 1-meter power in the linear and piecewise linear log distance pathloss model (Part of a farfield model)**
- **Power map may include phenomenology in addition to antenna gain (e.g. insertion loss, environmental effects,…)**

Power +  + 

dBm $\quad dB/Hz \quad dB/m^2$

= power spectral flux density $dBm/(Hz \cdot m^2)$



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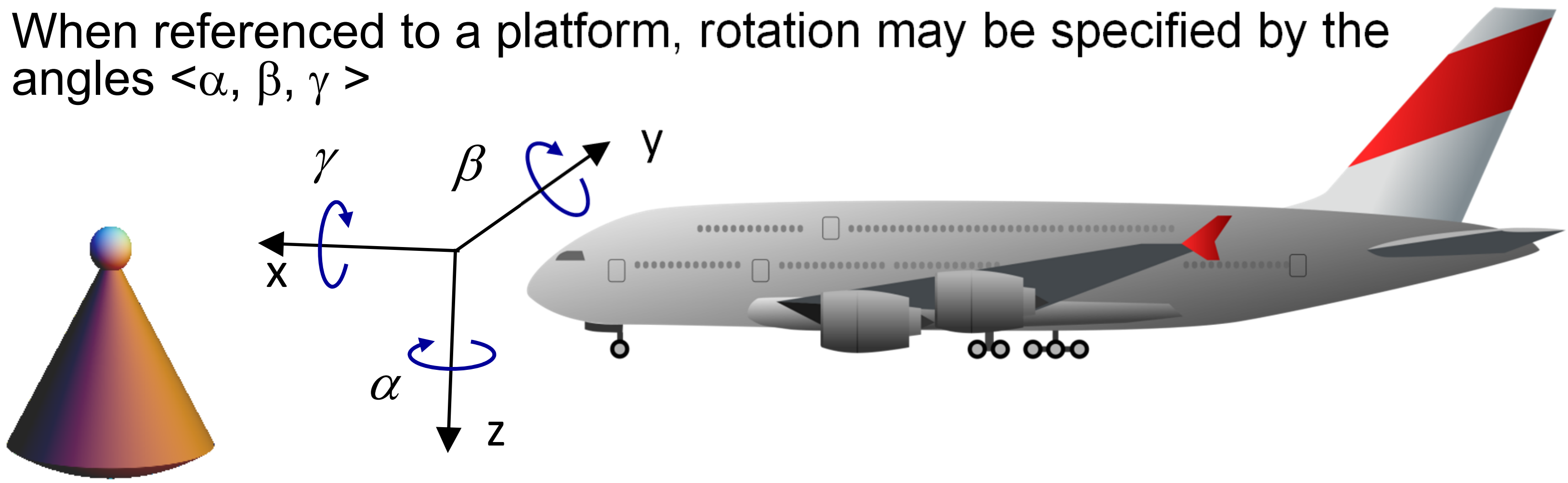
Power Map – Continued - 3

- **Usually, the coordinate system of the power map is the same as the coordinate system of the propagation map**
- **Exceptions**
  - When referenced to a platform, rotation may be specified by the angles <α, β, γ >



  - Direction may be fixed toward a point (antenna steers as the platform moves always pointing in the direction of the specified point)
  - Concentric maps used to specify scanning of directional beams, the outer map indicates the scanning region (usually the same as the propagation map) and the inner map defines the directional beam that is scanned

Probability data type

- **Used in many of the modeling constructs and is associated with particular aspects of the constructs**
- **Data type tries to clarify what probability means in the model**
  - Approach: cumulative versus alternative

  - Nature: fleeting versus persistent
    - For the fleeting nature, the probability refers to the fraction of time in a state and being in any state is momentary (Quantified by a maximum dwell time)
    - For the persistent nature, the probability refers to the likelihood of arriving at a state and being in that state may persist
  - Derivation: judgment versus estimated versus measured
- **By default all alternatives are used in computing compatibility**
- **Consideration of probability requires peer-wise agreement on the method**
- **Probabilities of different construct types are considered independent**

Using probability with the power construct

- **The probability element supports identifying a power distribution for systems that adapt their power or the specification of the probabilities of a collection of alternative discrete power levels**

Using the cumulative approach and fleeting nature for the use of a set of power levels

Power Level	Probability
20 dBm	1.00
17 dBm	0.97
14 dBm	0.95
11 dBm	0.80
8 dBm	0.50
5 dBm	0.30
2 dBm	0.10

UE Spectrum Masks - 1

- OFDM allows the mask to be modeled by evenly dividing the total power across the channel BW.
- 99% of the total power is within the channel BW.
- OOB emission limits provided in LTE spec.
- Shifted versions of the UE masks are provided to account for different Total Power levels dependent on the cell type.

Table 6.6.2.1.1-1: General E-UTRA spectrum emission mask

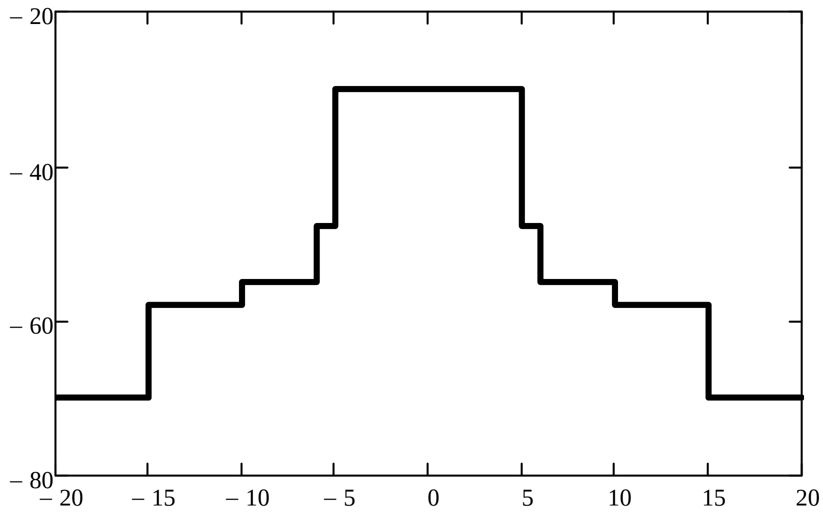
Frequency bands from the edge of the bandwidth

	Spectrum emission limit (dBm)/ Channel bandwidth						
Δf_{OOB} (MHz)	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Measurement bandwidth
± 0-1	-10	-13	-15	-18	-20	-21	30 kHz
± 1-2.5	-10	-10	-10	-10	-10	-10	1 MHz
± 2.5-2.8	-25	-10	-10	-10	-10	-10	1 MHz
± 2.8-5		-10	-10	-10	-10	-10	1 MHz
± 5-6		-25	-13	-13	-13	-13	1 MHz
± 6-10			-25	-13	-13	-13	1 MHz
± 10-15				-25	-13	-13	1 MHz
± 15-20					-25	-13	1 MHz
± 20-25						-25	1 MHz

Band resolution across which power is dispersed

UE Spectrum Masks - 2

Frequency (MHz)	Power (dB/10 kHz)
$f_c - 20$	-70
$f_c - 15$	-70
$f_c - 15$	-58
$f_c - 10$	-58
$f_c - 10$	-55
$f_c - 6$	-55
$f_c - 6$	-47.77
$f_c - 5$	-47.77
$f_c - 5$	-30
$f_c + 5$	-30
$f_c + 5$	-47.77
$f_c + 6$	-47.77
$f_c + 6$	-55
$f_c + 10$	-55
$f_c + 10$	-58
$f_c + 15$	-58
$f_c + 15$	-70
$f_c + 20$	-70

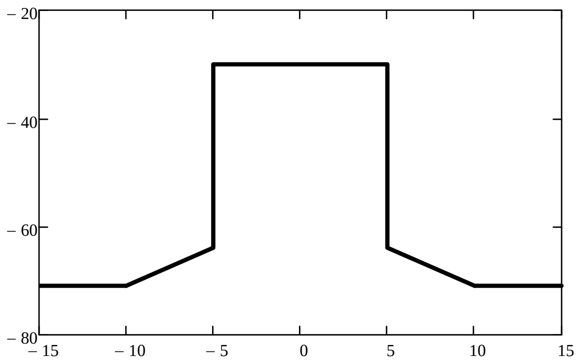


BS Spectrum Masks

- **Due to "better" RF hardware, the BS spectrum masks have better adjacent band rejection**
- **LTE spec provides OOB emission limits for Picocells and Femtocells.**
- **A shifted version of the Femtocell is used for the Enterprise Femtocell which accounts for the higher Total Power.**

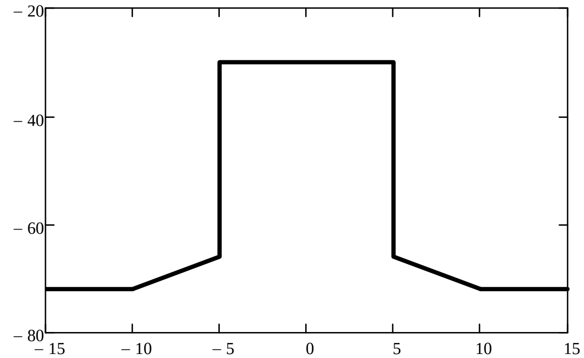
Picocell

Frequency (MHz)	Power (dB/10 kHz)
$f_c - 15$	-71
$f_c - 10$	-71
$f_c - 5$	-64
$f_c - 5$	-30
$f_c + 5$	-30
$f_c + 5$	-64
$f_c + 10$	-71
$f_c + 15$	-71



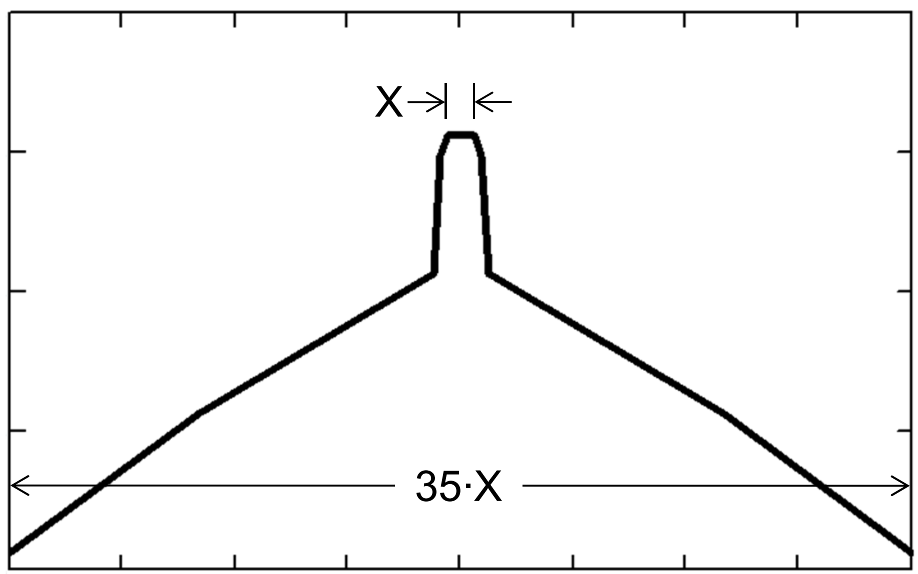
Femtocell

Frequency (MHz)	Power (dB/10 kHz)
$f_c - 15$	-72
$f_c - 10$	-72
$f_c - 5$	-66
$f_c - 5$	-30
$f_c + 5$	-30
$f_c + 5$	-66
$f_c + 10$	-72
$f_c + 15$	-72



A typical radar spectrum mask

- **High power transmissions make out of band emissions important**
  – A nominal X MHz bandwidth signal has a ~35X MHz mask



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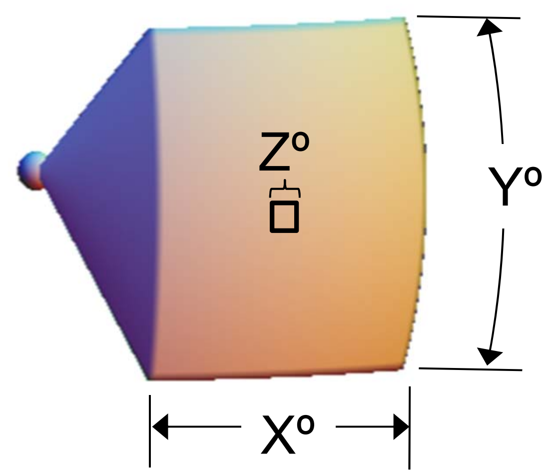
Combining Antenna Directionality, Scanning, and Pulsing into a Duty Cycle

- **Highly directional nature of the radar antenna and its scanning prevents receivers from taking the full brunt of the pulses in most operations**
  - Assuming constant direction of radiation, the duty cycle is

$$DC = (\text{pulse rate}) \times (\text{pulse duration})$$

  - Assuming a search over a X° azimuth a Y° elevation, and a Z° beamwidth, the duty cycle is

$$DC = \left(\frac{9\text{sectors}}{\frac{X}{Z} \cdot \frac{Y}{Z}} \right) \times (\text{pulse rate}) \times (\text{pulse duration})$$

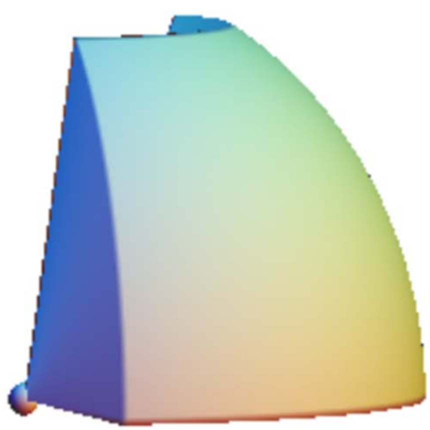


Radar

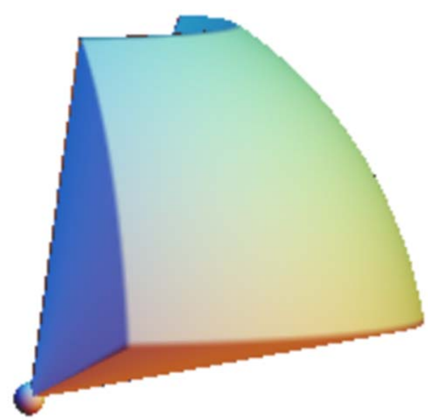
- **Transmitter modeling**
  - Scanning and pulsing can be represented as a low duty cycle signal
    - Spectrum masks uses frequency hopping mask with a dwell time and revisit time that is typical for any particular receiver (less than the actual pulse rate)
    - Power map shows the entire region of scanning

Radar - 2

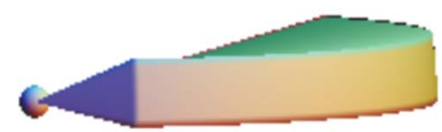
- **Transmitter modeling**
  - Scanning and tracking can be represented as a probabilistic event with a different pulse rate
    - Uses alternative persistent probabilities



99% at scanning rate



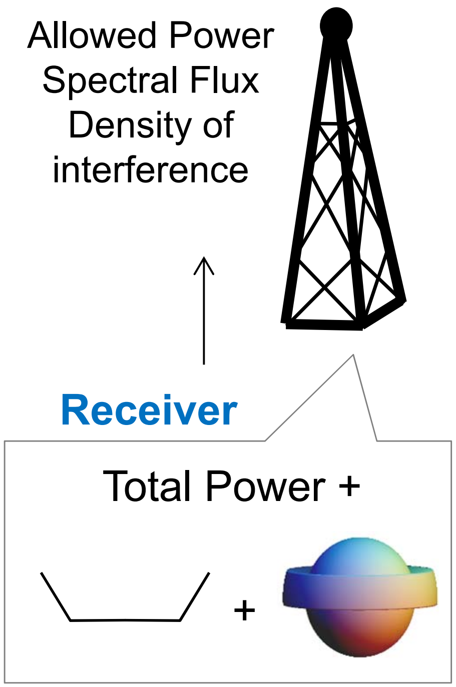
0.999% at tracking rate



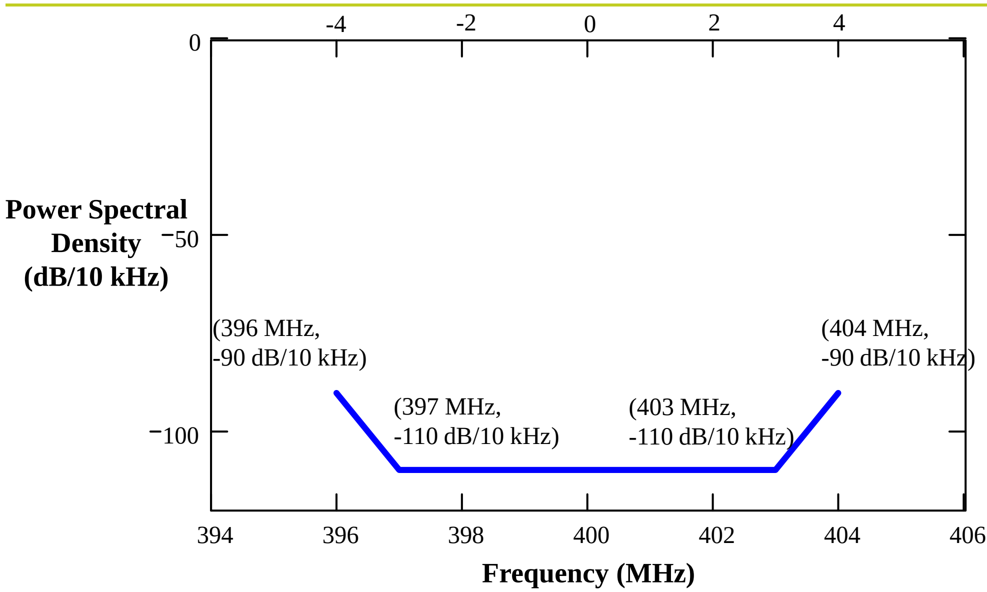
0.001% at tracking rate

Receiver Power Spectral Flux Density

- **Captured using three constructs**
  - Total power
  - Underlay mask
  - Power map
- **May divide a model up into different spaces with each having a different set of constructs for power spectral flux density**
- **Systems having multiple receivers**
  - Model each individually
  - Model a set of mobile receivers (e.g. data links and mobile ad hoc networks) by a single model and a space
- **Receiver modeling is not well defined**



3 – Underlay Mask



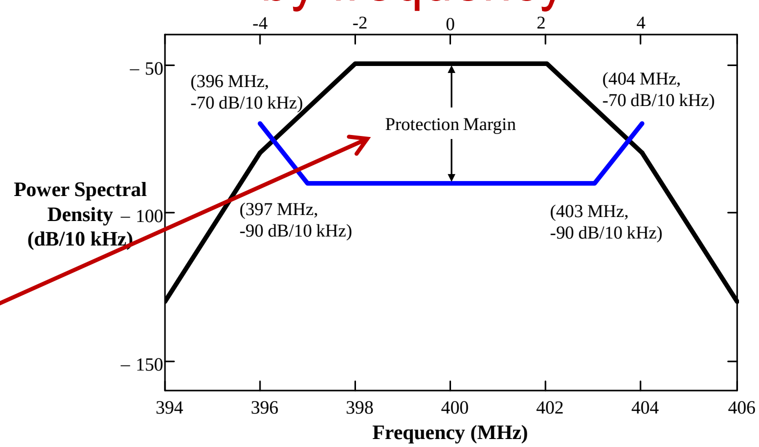
A list of inflection points that form a mask. Each point consists of a frequency and relative power. A resolution bandwidth conveys the spectral density of the power terms.

(396, -90, 397, -110, 403, -110, 404, -90)

BW = 10 kHz

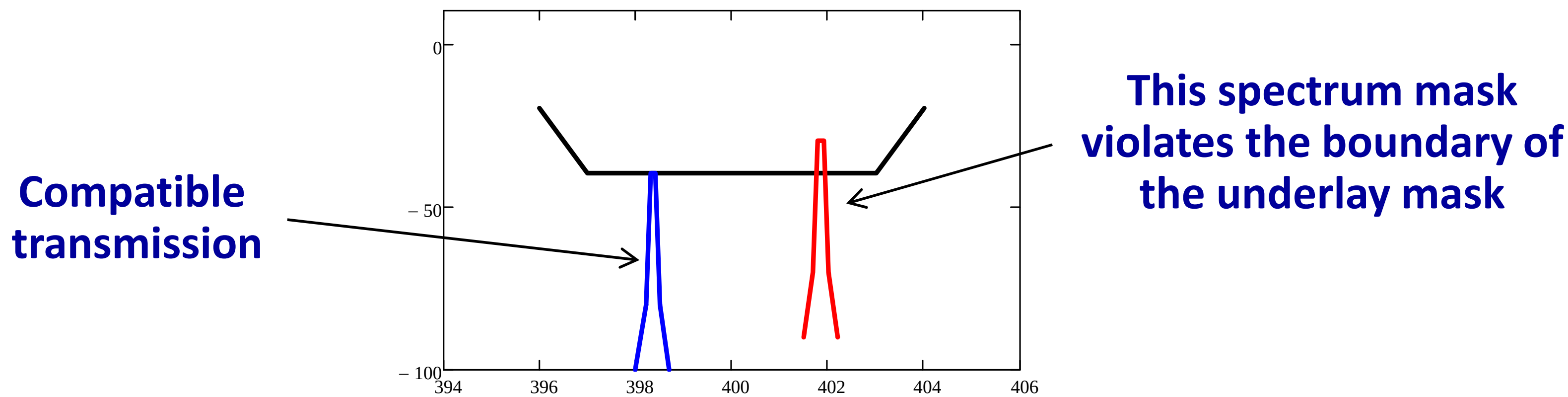
Specifies limit to the allowed interference by frequency

Together with the spectrum mask specifies the protection margin

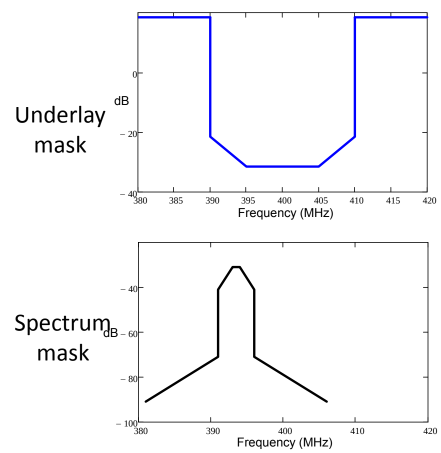


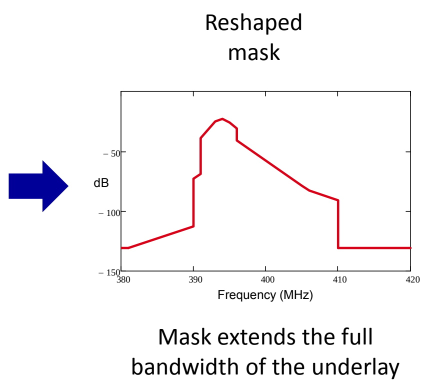
Two Methods of Mask Interaction

- **Maximum power density method (graphical)**



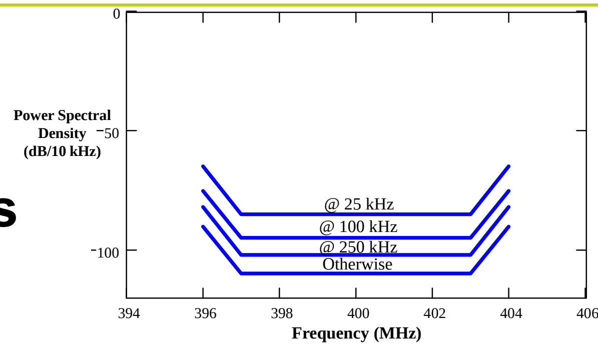
- **Total power method**
  - Underlay masks defines a filter which operates on the spectrum masks to determine the total energy that enters a receiver
  - Compatible if below a threshold





Underlay Mask Variants

- **Variants of the underlay mask allow identifying differences in robustness to interference based on bandwidth, frequency hopping, and duty cycle of interfering signals**
- **In compatibility computations the spectrum masks are mapped to the least restrictive underlay mask for which they meet the criteria of use**



Multiple Mask Structure

$(396,-65,397,-85,403,-85,404,-65)$ @ 25 kHz

$(396,-75,397,-95,403,-95,404,-75)$ @ 100 kHz

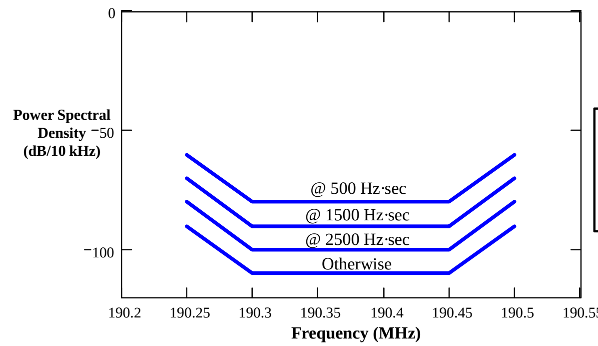
$(396,-82,397,-102,403,-102,404,-82)$ @ 250 kHz

$(396,-90,397,-110,403,-100,404,-90)$

Single Mask with Offset Data Structure

$(396,-90,397,-110,403,-100,404,-90)$

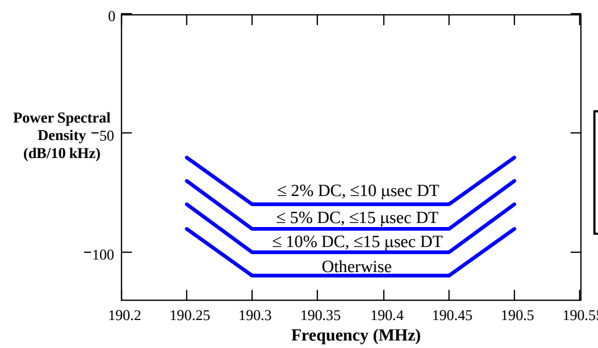
$(25,25,100,15,250,8)$



Data Structure with Bandwidth-Time Product Ratings

$(190.25,-90,190.3,-110,190.45,-100,190.5,-90)$

$(500,30,1500,20,2500,10)$



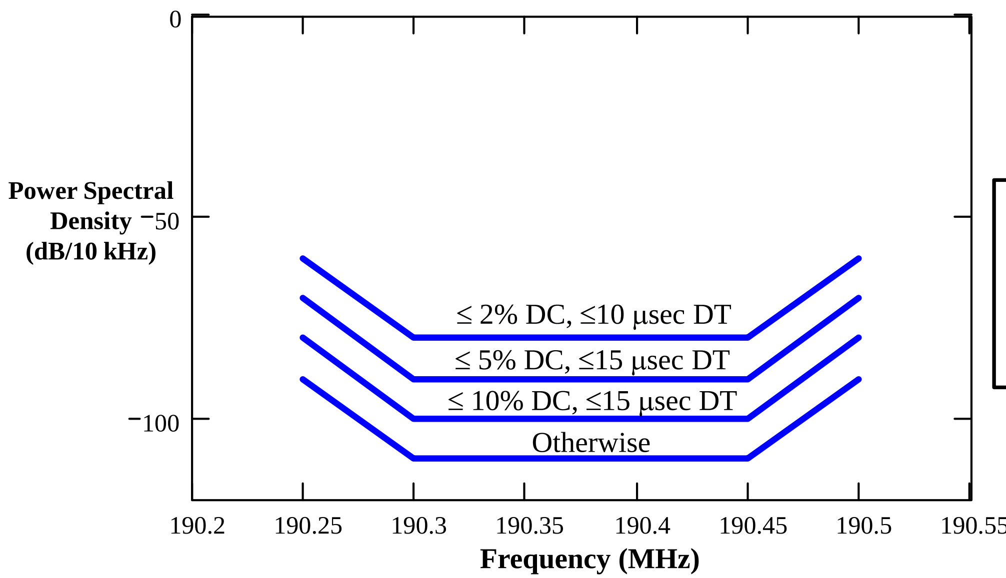
Data Structure with Duty Cycle Ratings

$(190.25,-90,190.3,-110,190.45,-100,190.5,-90)$

$(0.02,10\ \mu\text{sec},30,0.05,15\ \mu\text{sec},20,0.1,15\ \mu\text{sec},10)$

Accounting for Duty Cycle

- **Used with either method of computing mask interaction**
- **Provide separate masks for different interference duty cycles**
  - A duty cycle is the fraction of time a signal is turned-on, on average
  - Each mask is qualified by a duty cycle and the maximum dwell time when the signal is being transmitted



Data Structure with Duty Cycle Ratings

$$(190.25, -90, 190.3, -110, 190.45, -100, 190.5, -90)$$

$$(0.02, 10\ \mu\text{sec}, 30, 0.05, 15\ \mu\text{sec}, 20, 0.1, 15\ \mu\text{sec}, 10)$$

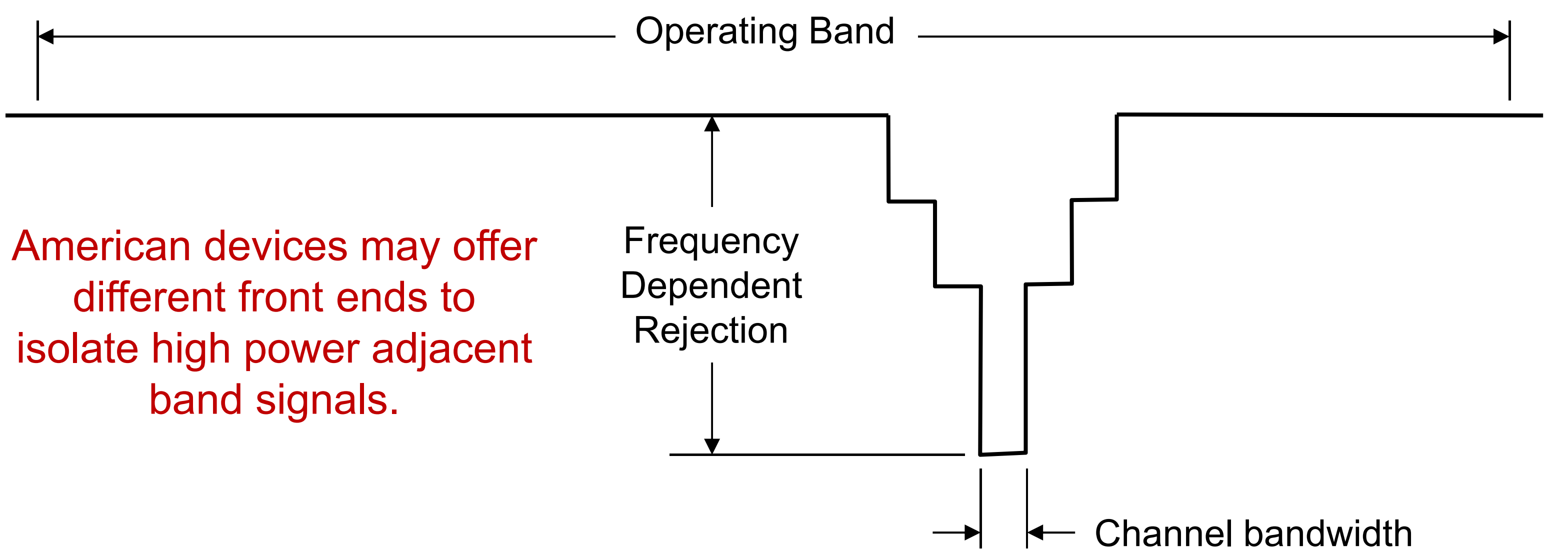
TD-LTE Underlay Masks

- **Interference thresholds in digital communication systems are based on acceptable packet error rates (PER) as determined by QoS requirements of higher level protocols.**
- **The higher the interference level, the greater the probability of receiving a bit in error.**
- **TD-LTE maintains a block error rate (BLER) of < 2% by adjusting coding and modulation.**
- **An interferer may cause block errors, but no more than 2%. This causes two distinct cases based on the interferer duty cycle:**
  - Duty Cycle > 2% : The underlay mask defines a threshold signal to interferer ratio. This threshold is determined by the probability of receiving the bit correctly in the presence of the interferer.
  - Duty Cycle < 2% : Low duty cycle allows loss of all blocks when the interferer is present. The underlay mask defines a threshold signal level to protect RF hardware.

The conversion between block error and duty cycle is not direct. It depends on both pulse duration and period. This estimate is based on understanding that radar pulses are both short and sporadic

Two-level Underlay Masks

- **TD-LTE operates in 200 MHz bands, for example**
  - Band 42: 3400 – 3600 MHz
  - Band 43: 3600 – 3800 MHz
- **We suspect that TD-LTE systems will be designed to move to channels anywhere in these bands and so the front end will allow energy to enter across the band and selective filtering in the IF sections will isolate the channel of interest**



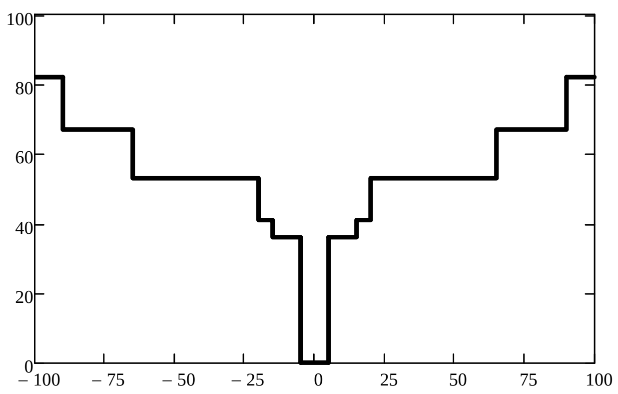
American devices may offer different front ends to isolate high power adjacent band signals.

TD-LTE Underlay Mask - 1
Duty Cycle > 2%

- **Mask levels provided based on the probability of receiving the data correctly in the presence of an interferer.**
- **LTE specs provide testable thresholds of**
  - In-channel identified by a reference sensitivity power

$$P_{RefSens} = N + SINR$$

    - N varies between base stations and handheld devices
    - SINR for a 2% BLER varies by modulation
  - Adjacent Channel (Ability to receive a desired signal given adjacent channel interference relative to the desired signal)
    - LTE specs provide an Adjacent Channel Selectivity of -33 dB
  - Blocking (Maximum interference power reference to the in-channel desired signal level)
    - LTE specs provide absolute power levels dependent on the offset from f_c.
- **We assume masks that are based on these testing requirements. Actual devices may perform better**

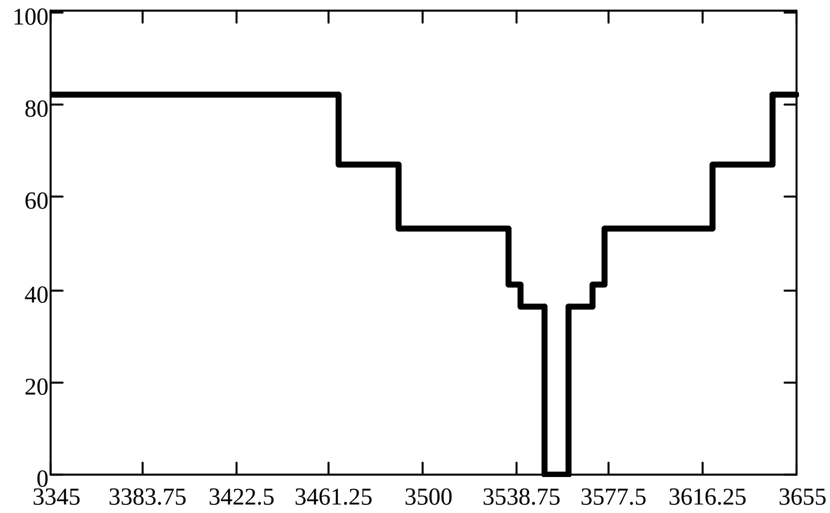


TD-LTE Underlay Mask Shape

Frequency (MHz)	Power (dB/10 kHz)
3400 - 55	p_r + 82
f_c – 90	p_r + 82
f_c – 90	p_r + 67
f_c – 65	p_r + 67
f_c – 65	p_r + 53
f_c – 20	p_r + 53
f_c – 20	p_r + 41
f_c – 15	p_r + 41
f_c – 15	p_r + 36
f_c – 5	p_r + 36
f_c – 5	p_r
f_c + 5	p_r
f_c + 5	p_r + 36
f_c + 15	p_r + 36
f_c + 15	p_r + 41
f_c + 20	p_r + 41
f_c + 20	p_r + 53
f_c + 65	p_r + 53
f_c + 65	p_r + 67
f_c + 90	p_r + 67
f_c + 90	p_r + 82
3600 + 55	p_r + 82

f_c = 3555 MHz

p_r = 0 dB/10 kHz



We are assuming the mask can be applied to both the >2% and the <2% cases but that the p_r will be different

TD-LTE Underlay Mask Power Reference

- **With duty cycles >2% case, p_r also depends on:**
  - Spread of power over bandwidth

$$=10 \cdot \log\left(\frac{rbw}{Bandwidth}\right)$$

  - If noise limited, the allowed introduction of noise

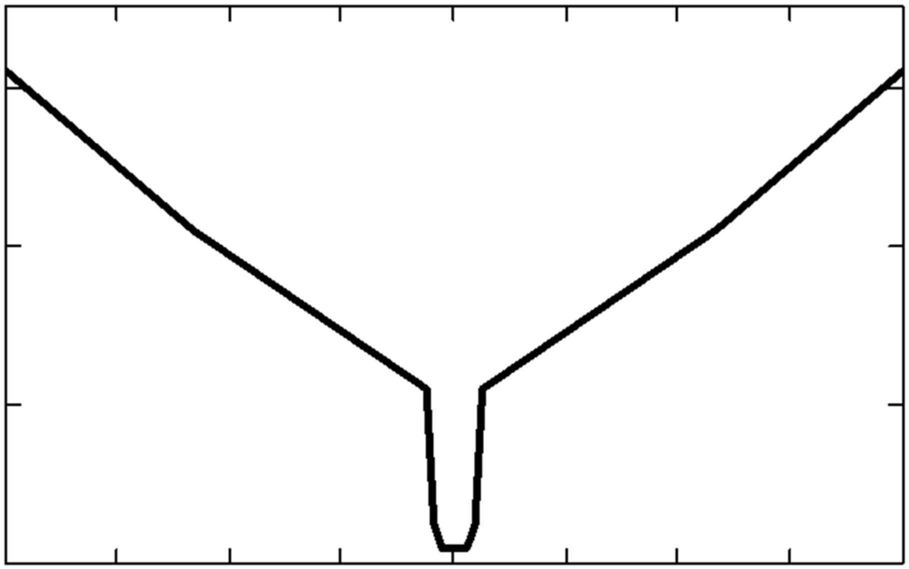
$$I_T = {}^{I}\!/_{N} + N \qquad I_T \approx \text{-100 dBm}$$

  - If interference limited, the average power the operator is willing to operate the system
    - A choice that compromises optimal LTE performance for the opportunity to use the spectrum
- **For low duty cycles (< 2%), use the power that can damage the equipment or cause a lingering effect**
  - We assume -25 dBm

Based on the spec for maximum received signal power which maintains performance

Radar underlay

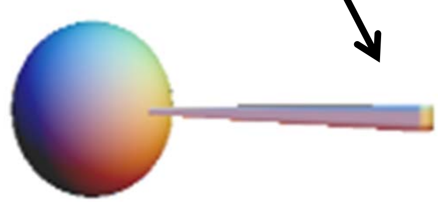
- **In a pinch the inverse of the spectrum mask may be used**
- **Mask may be associated with particular protocols or policies**
  - Can adjusts mask power levels to account for resilience against particular known interferers based on signal processing at the radar



Radar Receiver Modeling

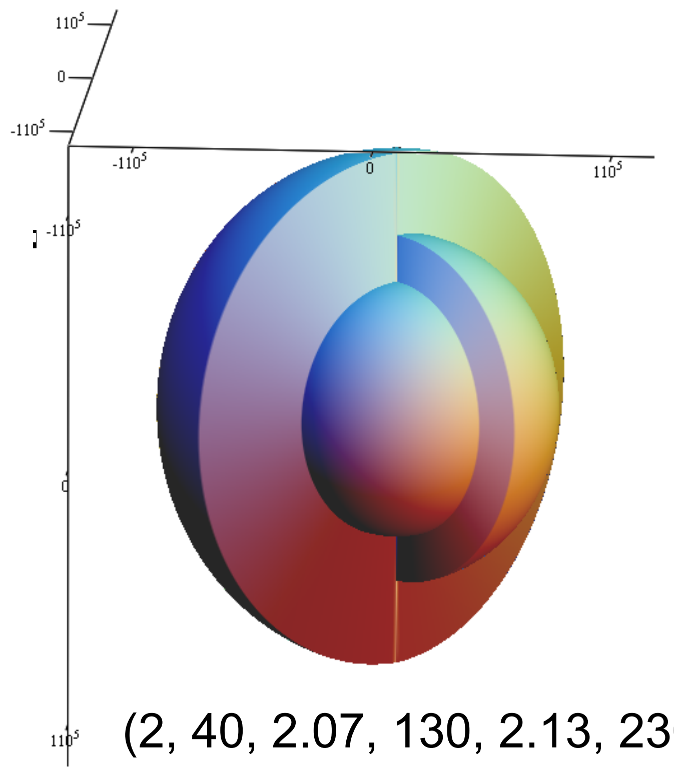
- **Receiver modeling**
  - Issue
    - Interference limited by the directionality of the beam
    - Beam can be pointed in many directions
  - Use hierarchical power map
    - Scanning region specified by one power map
    - Antenna pattern specified by the second map

This beam may be pointed anywhere in these directions



MITRE

5 – Propagation Map



(2, 40, 2.07, 130, 2.13, 230, 2, 0)

A variable length 1 x n array that assigns parameters of a pathloss model to solid angles about a point. There are two models, linear and piecewise linear on a dB to log distance

Specifies the rate of attenuation by direction

(2, 550, 3.2, 40, 2.07, 400, 3.5, 130, 2.13, 350, 3.3, 230, 2, 550, 3.2, 0)

In a linear model a pathloss exponent is assigned to each solid angle. In a piecewise linear model a pathloss exponent, a distance, and a second pathloss exponent is assigned to each direction

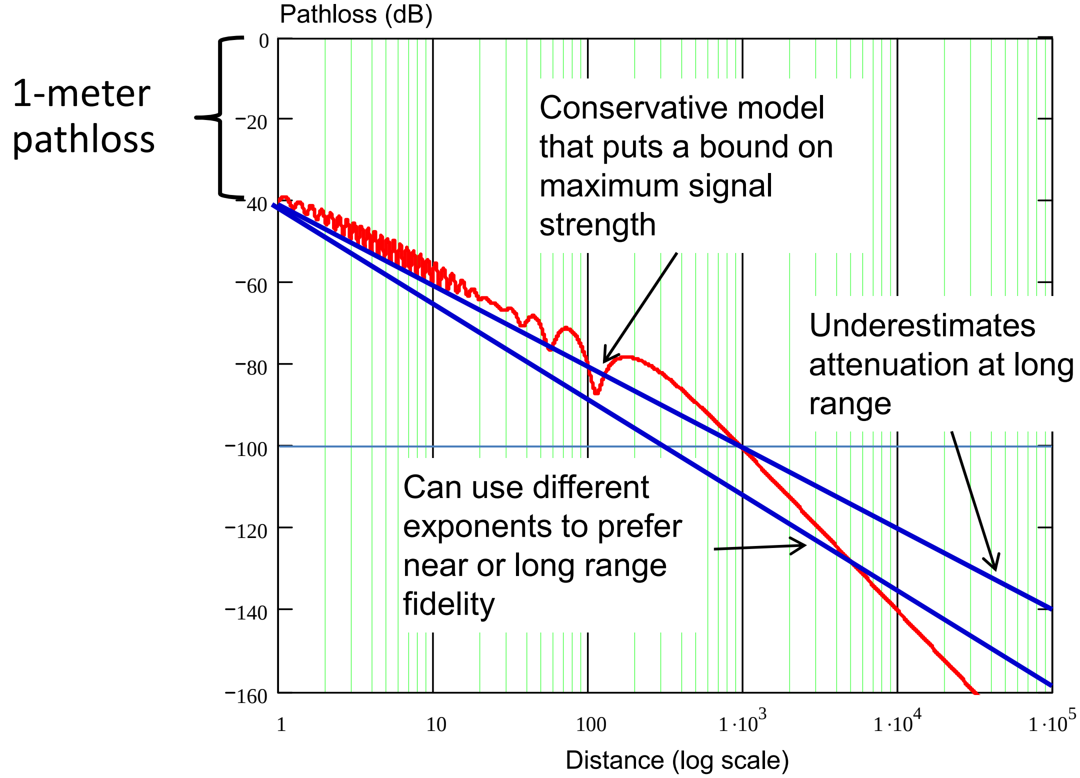
Propagation Modeling Objectives

- **Many tools invest heavily in propagation modeling**
  - Databases of terrain features
  - Models that capture the effects of the terrain features and manmade objects
- **An important feature of spectrum consumption modeling is that the propagation model is a part of the model of spectrum use rather than just a part of a tool**
  - Eliminates the need to have a common tool
    - Does not require a common database of terrain
    - Allows innovation in propagation modeling within tools
    - Spectrum use decisions can be made at devices
  - Abstraction chosen to allow tractable computations of compatibility
  - Common assessments of compatibility everywhere
- **Modelers may use tools of their choice to create propagation maps**
- **Propagation modeling is artful**
  - Many features in SCM to support differentiation of propagation effects
  - Modeling may become a service in a system
  - Models may be negotiated between parities

Tools to support modeling is the next innovation

Propagation Map
Linear Log Distance Pathloss Model

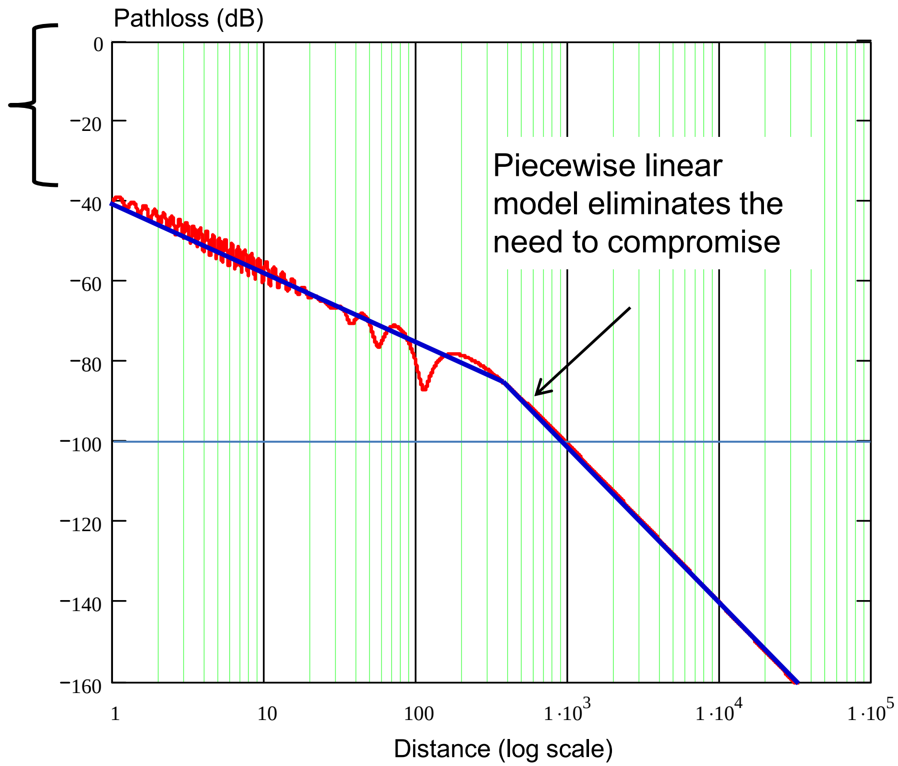
- **Conveys the rate transmissions attenuate by direction, by providing the pathloss exponent of a log distance pathloss model**



$$RP(d) = RP(1m) - 10n\log(d)$$

Propagation Map
Piecewise Linear Log Distance Pathloss Model

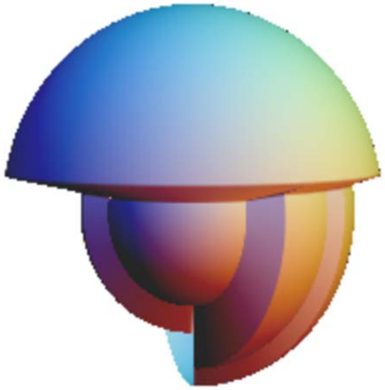
- **Map stores two exponents and a breakpoint distance per direction**



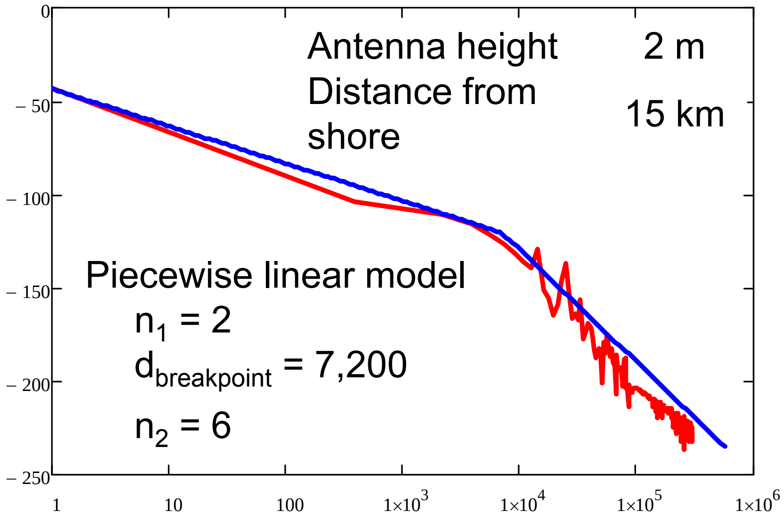
$$RP(d) = \begin{cases} RP(1m) - 10n_1 \log(d) & d \le d_{breakpoint} \\ RP(1m) - 10n_1 \log(d_{breakpoint}) - 10n_2 \left(\log(d) - \log(d_{breakpoint})\right) & d > d_{breakpoint} \end{cases}$$

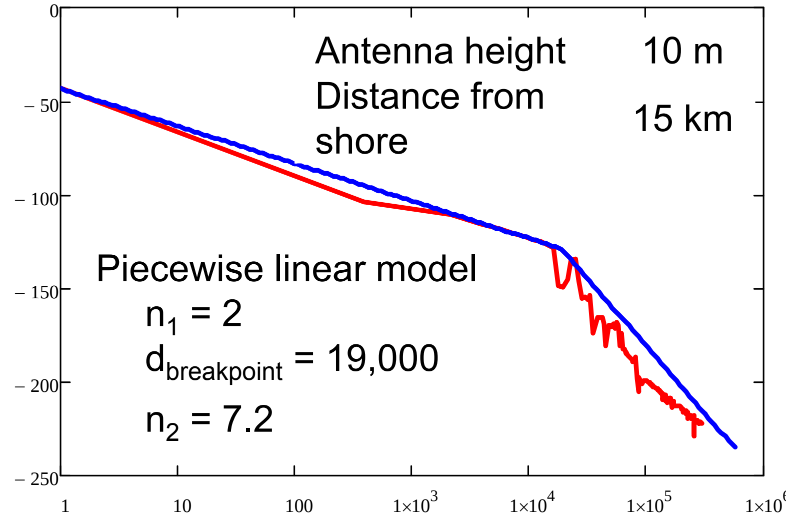
Propagation model alternatives

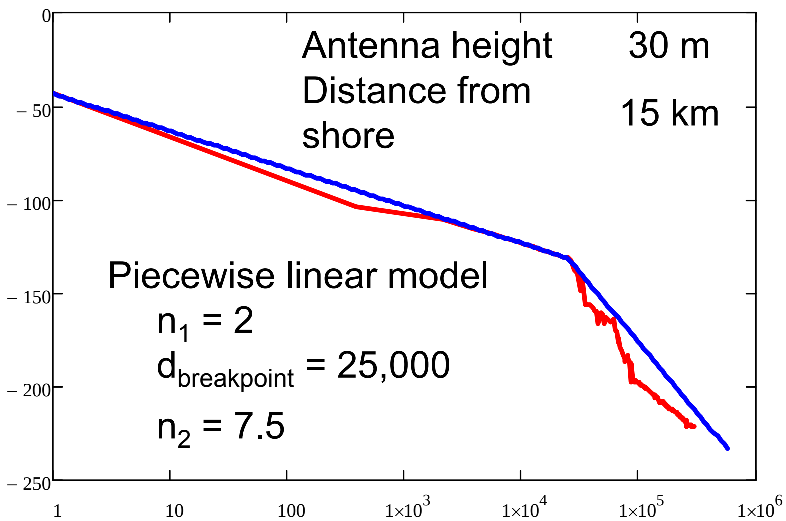
- **Generally**
  - Standard propagation map differentiating by azimuth and elevation
- **Long range terrestrial**
  - Maps are receiver antenna height rated
  - Differentiate by azimuth but not by elevation
  - Can capture ducting effects
  - Models may have several maps, each rated for a different height
    - Pathloss is interpolated for height in-between map ratings

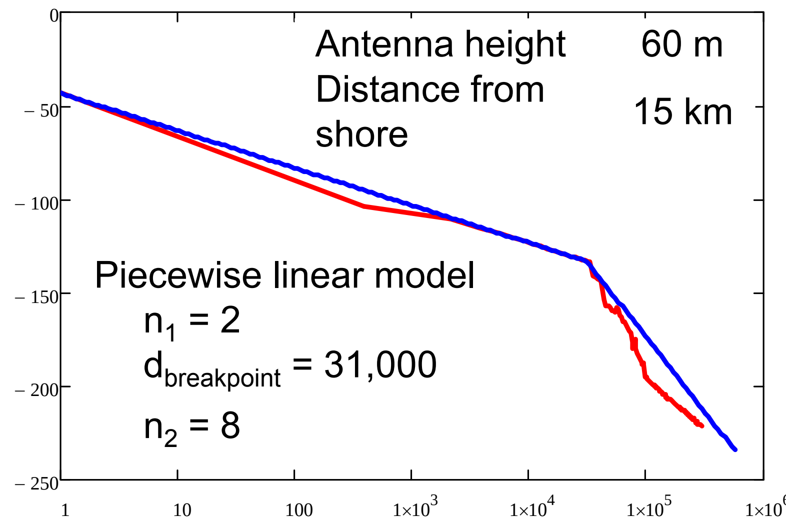


Comparison of TIREM Predictions and Piecewise Linear Models - 1









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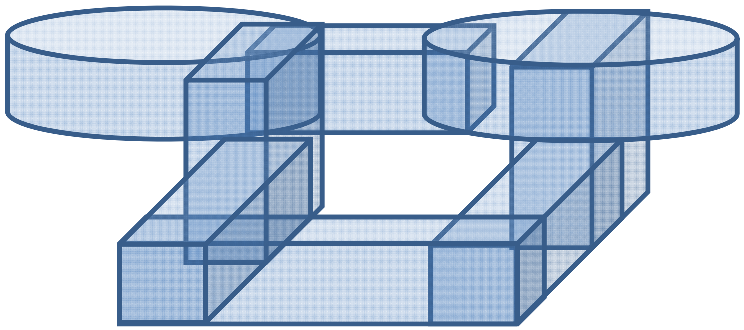
8 - Locations



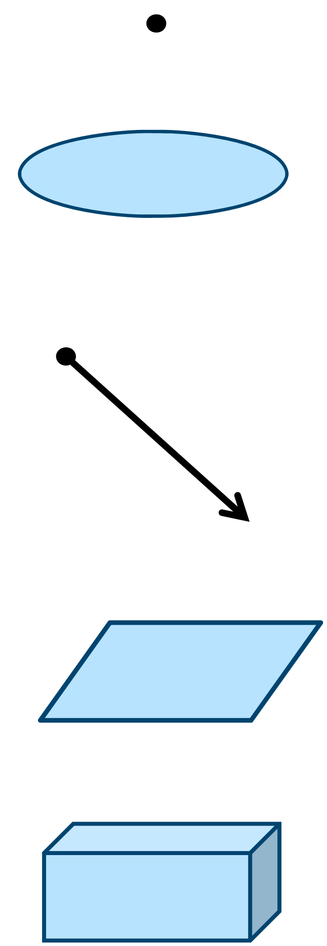
The use of smaller volumes to capture segments of a mission

Locations may be points, surfaces, volumes, trajectories, or orbits (piecewise tracks)

Identifies where systems are operated

Modeling Locations

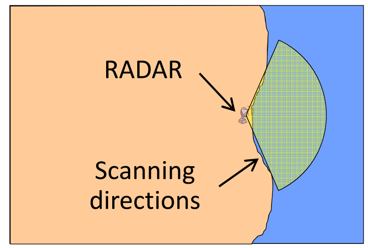
- **TD-LTE**
  - Base stations at points
  - UE on surfaces or in spaces
- **Radars**
  - Tracks provide greatest accuracy
  - Surface areas and volumes support abstracting specific locations or bounding locations when they are uncertain



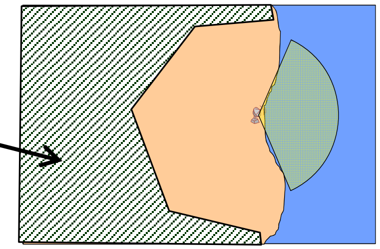
Protecting Sensitive Details

- **Models that reveal opportunities for secondary use may be permissive or restrictive**
- **Modeling provides multiple options on how to model spectrum reuse**
- **Spectrum modeling can evolve to reveal more reuse opportunities once parties come to trust each other**

Radar Scenario

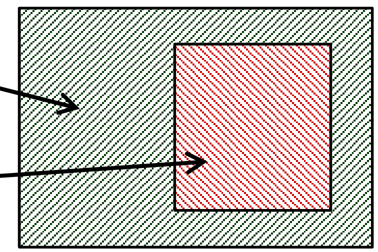


You can use the spectrum here



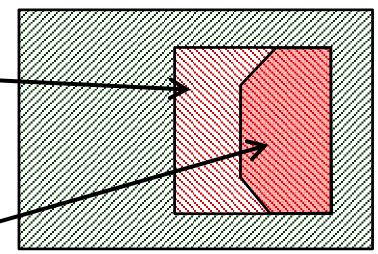
You can use the spectrum here

If you do not violate the restrictions of this model

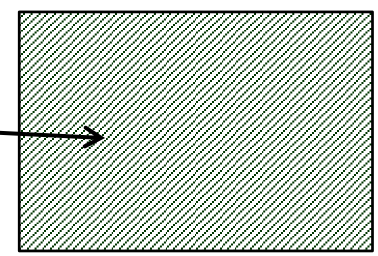


Less restrictive models in the bigger space are designed to prevent interference in the low gain directions

Transmitter and receiver models in this space are directional and more restrictive



You can use the spectrum here if you use protocol x or policy y



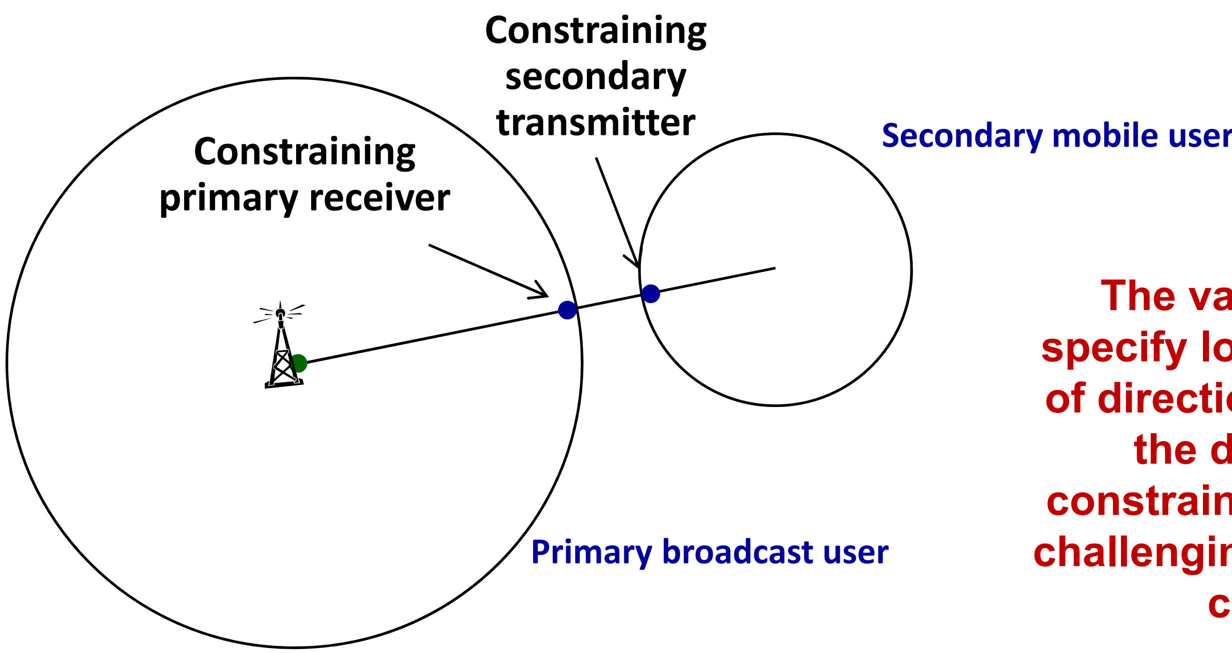
Conclusion

- **SCMs can capture the unique features of radars and broadband systems that allow sharing**
  - Pulsing low duty cycle signals
  - Scanning highly directional antennas
  - Tolerance of low duty cycle interference
  - Adaptive power and clutter effects
  - Tolerance to particular interferers because of signal processing or protocol behaviors
- **Modelers anticipate the features that support sharing and reveal those features**
- **Modeling allows a reasonable level of obfuscation of system capabilities and operations**
- **Many types of models can be made for the same system and operational use allowing different levels of sharing**
  - SCMs are a means to communicate boundaries of spectrum use and policies for spectrum use
  - Agreeing to use SCM is not a commitment to a particular sharing policy

Backup

General Process for Computing Compatibility

- Determine if uses will overlap in time and spectrum
- Determine the constraining points (the point of primary operation and the point of secondary operation that most restrict the secondary user)
- Compute the allowed transmit power of the secondary



The variety of means to specify locations and the use of directional antennas make the determination of constraining points the most challenging part of computing compatibility